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MECHANISM OF ABRASION PROFILE DEVELOPMENT IN THE COASTAL ZONE OF THE SEA

By Yu.D. Shuisky

An analysis of the data on abrasion shore dynamics reveals the existence of three main genetic types of active cliffs:

1. Abrasion cliffs with rockfalls, characterized by wave erosion of the base of the cliff, formation of wave-cut notches and grottoes, steepening and hence destabilization of the shore slope, and resultant rockfalls into the sea under the influence of gravity, producing a gentler and restabilized shore slope.

2. Abrasion cliffs with landslips, which are also destabilized by wave erosion of the base. In this case, however, abrasion also helps to reduce the load on the slope, which leads to slipping of blocks of rock, the protrusion of a tongue of talus into the sea, erosion of the tongue by waves and a new disturbance of the equilibrium profile.

3. Non-wave-cut cliffs, where wave and non-wave factors operate at equal speed, with the former acting on the base of the slope and the latter on the remaining part. As a result the cliff retreats while the general form of the transverse profile is preserved and there is no apparent change in the steepness of the profile through time.

As can be seen, active cliff development requires the constant maintenance of a fairly steep profile, so that rockfalls or slips occur under the influence of gravity. And it is abrasion processes that keep the profile in such a state. It is generally accepted [2, 4] that active cliffs retreat in the course of their development until, in

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the fullness of time, an abrasion platform wide enough to act as a wave break has been formed on the underwater slope in front of them. Following this, the rate of retreat of the cliffs gradually slows as the platform widens, and the abrasion shore passes through a three-stage cycle of development:"youth", "maturity" and "old age" (Fig. 1). Finally, the shore abrasion profile reaches a point at which the cliff "dies".

A similar scheme of abrasion shoreline development was proposed early on by D W. Johnson [9]. He also believed that the abrasion products were swept out to the underwater slope where they formed a wave-built terrace of accumulation .This scheme was adopted in principle by other investigators as well, but they shortened the cycle of cliff development. Zenkovich [2] and Leont'ev [4] concluded on the basis of numerous field studies that the stages of "maturity" and "old age"may occur but are not characteristic. The attainment of these stages is hampered by relative fluctuations in sea level, as represented on the geological time-scale by the phenomena of transgression and regression. Hence the coastal zone is unable to attain a state of equilibrium in the vast majority of cases because transgressive-regressive fluctuations in sea level constantly alter the equilibrium profile, maintaining tension between the various factors in abrasion profile development and keeping the rates of the coastal-marine processes fairly high. This is what prevents the shores from reaching the stage of "old age".

There is no doubt that this critique of D.W. Johnson's views is correct. If we take stretches of shoreline made of hard rock, then indeed, before an equilibrium profile is produced, the sea level will rise or fall, the sea will submerge a new piece of land, the waves will attack the areas of newly formed relief, and the shore processes will receive a fresh impetus. Hence, *pace* Johnson, the land cannot in the final analysis be truncated by abrasion.

As regards stretches of shoreline made of soft, loose rock, the processes of abrasion follow a pattern different from the one illustrated in Fig. 1.

Many years of fixed-site observations [3, 8] showed that the rate of retreat of active cliffs often reaches several metres per year. If we compare this figure with the rates of relative fluctuation in sea level, we find that they differ by 2–3 orders of magnitude, and sometimes even more. In other words, before the sea level has risen or fallen a few centimetres, which is evidently not enough to alter the equilibrium profile, the cliff may have retreated several hundred metres. This is especially true if the shores are composed of clayey, loamy, sandy-loamy or sandy materials. Examples of this can be seen on certain stretches of coast on the Sea of Azov (northern and eastern parts), the Black Sea (near Cape Burnas, between the Tendra peninsula and

Dzharylgach island, north of the mouth of the Al'ma River), the Baltic (the Sambiiskii peninsula, north of Pavilosta), and many other seas. It is on such easily eroded coasts as these that a sufficiently wide abrasion platform can form before the sea level rises or falls far enough to provide a fresh impetus for the development of a new equilibrium profile. On such stretches of coast the cliffs never become inactive and abrasion continues to operate. It is quite clear that the conventional scheme of development does not fit such coasts since it does not take such circumstances into account.

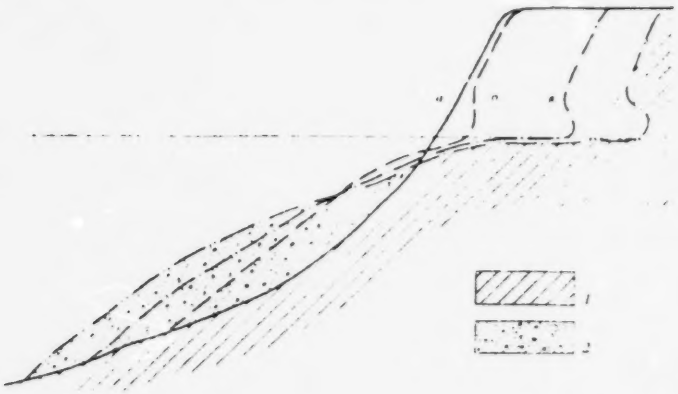

Fig. 1. Classical scheme of the long-term development of an abrasion shoreline
1 – bedrock; 2 – wave-built terrace made up of sediment; a – initial curve of transverse profile; b, c, d – curves marking the different stages in the development of the abrasion profile.

Another weakness is that the old scheme does not take into consideration the dynamics of the underwater slope on the abrasion shore. This is due to the fact that until recently we had no quantitative data on bench cutting We now know that under the influence of abrasion the depth of the water in front of an active cliff does not remain constant as it must have done during the formation of the abrasion platform and the retreat of the cliff. While the surface of the platform is being formed the latter must be undergoing continual erosion, and at rates far higher than conventionally assumed. Indeed, when observations were conducted on the dynamics of clay benches using precise levelling and references points on the sea bed, it was found that the rates of abrasion were 0.2–0.4 m/year at depths of 3–4 metres in some years, with a maximum of up to 0.7–0.8 m/year at depths of 0–1.5 m. Afterwards it

became clear why, on any one profile, the depth increased considerably within a comparatively short interval of time (up to 15–20 years), while the form of the profile altered (Fig. 2).

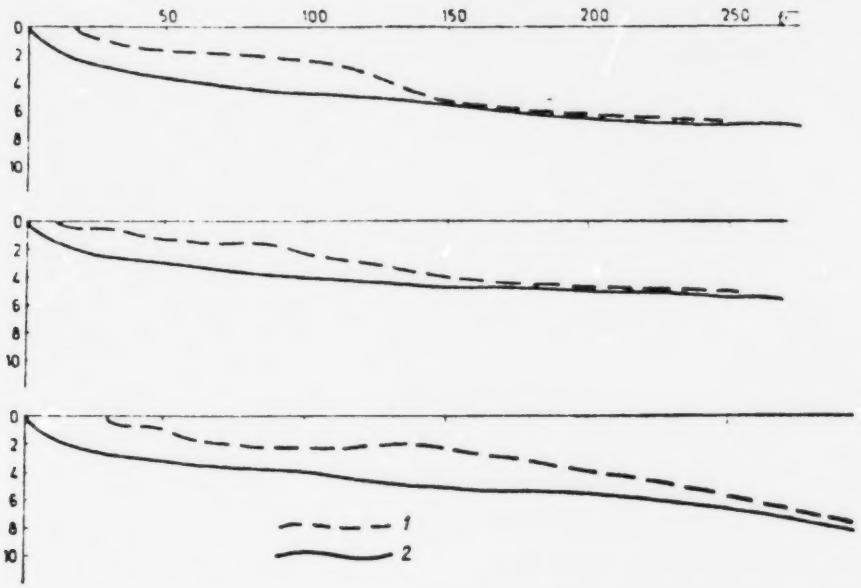

Fig. 2. Present profiles of the underwater slope of the Black Sea based on the results of surveys conducted in 1954 (1) and 1970 (2) at different points on the west coast of the Crimean peninsula

Nevertheless, none of a series of annual observations at a permanent site showed that the rates of abrasion of cliffs and benches in any given year were equal to the rates in other years. This state of affairs can be ascribed to fluctuations in the hydrometeorological regime, the sediment balance, the geologic structure and other factors. The results of investigations carried out on shores composed of argillaceous rocks in the northwest region of the Black Sea suggested that for any given stretch of coast the rate of abrasion depends largely on the volume of sediment contained in the beach at the base of the cliff (Fig. 3). Since the dynamics of the beaches under such conditions are an indicator of the combined effect of all coastal-marine factors acting on the dynamics of the coastal zone [1], the beach can be regarded as the main regulator of the mechanism of short-term development of the erosion profile. This conclusion is valid for cliffs both with rockfalls and with landslips. The dispersal of

the points on the graph in Fig. 3 is due to variation in the height of the cliffs at different points along the shores investigated, variation in the gradient of the underwater slope and the average parameters of the waves approaching the shore, differences in the physico-mechanical properties of the various types of rocks forming the cliffs, and other factors.

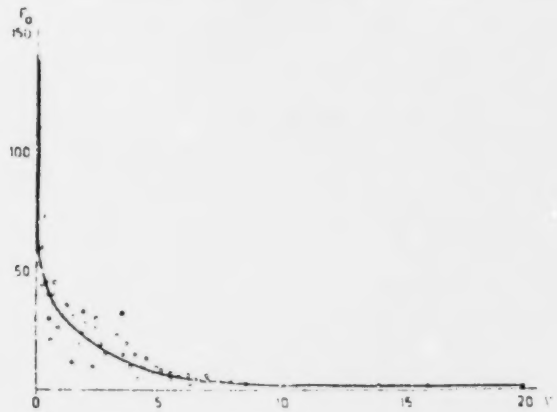

Fig. 3. Graph of the rates of abrasion of a cliff (W_a, metres per year) in relation to the volumes of sediment contained in the beaches at the base of the cliff (F_a, m^3 per linear metre of shoreline)

The rate of erosion of cliffs and benches is not always as high; as mentioned earlier, it fluctuates widely through time. On any given stretch of coast the annual rates of erosion are generally higher when the foot of the cliff is bounded by a comparatively narrow beach or no beach at all. Erosion slows considerably or even stops altogether when the beach is wide. Moreover, the beach also protects the underwater slope, though only upper end of the latter, in the waterline zone of the abrasion platform Hence the abrasion rate of the solid argillaceous rock surface of the bottom also fluctuates: it is higher when the bench is bare and lower when it is covered with sand.

Utilizing the field observation data cited above and some of the conclusions that can be drawn from them, we can describe a formalized model of the mechanism by which the abrasion profile of the coastal zone is produced. We are assuming that the hydrometeorological conditions are uniform and remain constant in time, that the shore and bottom have the same lithology, and that the topography of the underwater slope is not complicated by minor microforms. By way of example we

shall use data from a study of shores subject to collapse, composed of argillaceous and easily erodible rocks having class IV–V abrasion resistance, according to Leont'ev's classification [4]. In developing the model we incorporated the following main assumptions of the theory of coastal development: (a) the development of cliffs is closely bound up with the development of the underwater slope (benches); (b) the evolution of the coastal zone always tends to the attainment of dynamic equilibrium with the existing hydrometeorological regime; (c) the development of the coastal zone is always uneven in time; (d) the rate of coastal-marine processes is always much higher than the rate of relative fluctuation of sea level, which is an underlying factor in the development of the coastal zone.

Let us imagine that in one of the stages of shoreline development wave processes begin to interact with a part of the land surface steep enough for abrasion to be initiated within that segment. Immediately, reworking of the land surface begins, and cliffs and benches are formed as in water reservoirs, or as depicted in Fig. 1. Since there is initially little sediment in the shore zone, the land surface is unprotected and abrasion proceeds at a fairly fast rate.

But as the abrasion platform develops, we are struck by two important points: (1) detritus is removed by the abrasion processes and added to the supply of sediment in the shore zone; (2) the shallow waterline zone of the platform widens as the shoreline retreats. When the platform is wide enough to constitute a wave break, sediment begins to accumulate at the base of the cliff in the form of a beach, and the wider the platform the wider the beach.

Field surveys on the sea (Fig. 2) and on reservoirs [5] show that the development of the profile of the waterline zone proceeds very rapidly in argillaceous rock, taking no more than 10–15 years owing to the high rate of abrasion. In time the platform-generating processes slow because the width of the platform gradually increases and becomes so great that it dissipates a great deal of the wave energy. As a result, the emerging beach causes a sharp drop in the rate of abrasion of the cliff (Fig. 3). At this time the waves have very little effect on the underwater slope because they can only attack the upper part to any appreciable extent, and that is protected by a veneer of sediment. It is important to note in this connection that uprush, which is a prominent factor in the reworking of cliffs and benches, ceases to play a part in the abrasion process.

For the same reason the effect of large waves on the upper part of the underwater slope is lessened, whereas the middle part, including the seaward slope (A) of the abrasion platform, continues to be attacked by large waves. Here the

greater steepness of the transverse profile (Fig. 4b) prevents or hinders the accumulation of sediment, so that there is no serious resistance to the waves and currents. Hence the morphology of the underwater slope and the distribution of sediment on it cause a kind of selective abrasion: the action of large waves at the beginning of stage **b** (Fig. 4b) leads to erosion of only the base and outer edge of abrasion platform.

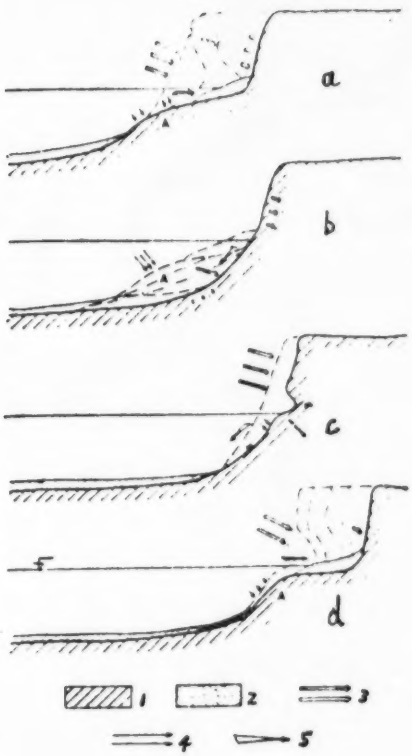

Fig. 4. Scheme of development of transverse abrasion profile in time. (not to scale)

a–d – stages in development of profile: 1) solid argillaceous rock; 2) coastal-marine sediments; 3) direction of retreat of cliff; 4) retreat of bench; 5) direction of transport of sediment. The dashed lines indicate the different positions of the profile during its development. The size of the arrows serves as a guide to the relative rates of erosion of the shore and bottom at different stages in the evolution of the abrasion profile.

Notwithstanding the comparatively low frequency of occurrence of large waves, abrasion of the base and outer edge of the underwater platform at the beginning of stage **b** occurs far more quickly than erosion of the cliff. Contributory factors here are the relatively large reserves of energy of high waves (h = 1.5 m) and the steeper angle of the underwater slope at the foot of the platform compared with the angles of slope of its surface. As is known [2, 4], on the steeper segments of the profile, the specific energy of the transformed waves is higher.

The zone of the interface between the upper and middle parts of the underwater slope A, to which the edge of the abrasion platform is normally confined, lies at a depth of about 3.5 metres, i.e. under the conditions obtaining in the north-west part of the Black Sea it lies on a segment of the transverse profile where the depth H = 2.0 h–2.5h (h being the mean annual long-term height of the large waves, equal to approximately 1.5 metres, H the depth of the sea). According to the results of observations of the wave and current regime in the coastal zone of the Black Sea (the regions of Odessa , the near-shore zone of the Danube delta, the Donuzlavskaya bar, the south coast of the Crimea, the Dzharylgach spit), it is precisely between the depths of 0 and 3.5 metres that the nearshore waters are most active and have a heightened capacity for abrasion and sediment transport.

Because of the selective action of waves and currents on the transverse profile, the platform has become eroded by the end of stage **b** (Fig. 4b), and the overall angle of the underwater slope has increased. Hence there is no longer as much sediment at the base of the cliff as there was. It has been carried away downslope and the beach is being eroded. Sediment accumulation occurs at greater depths (H = 2.5h), and at this time, at the beginning of stage **c** (Fig. 4c), abrasion of the cliff is intensified, since the beach at its base is no longer wide enough to inhibit it. In stage **c** the transverse profile acquires an aspect similar to that in stage **a**.

In stage **d** (Fig. 4d) the process of abrasion profile development begins anew: the rate of cliff erosion is maximal, the abrasion platform is actively excavated, the angles of slope of the bottom become gentler at depths of less than H = 2.5h, and beach sediments accumulate to cover the foot of the cliff and the underwater slope at depths of less than H = 2h, after which abrasion operates most rapidly on the bench. The cycle of abrasion profile development described above is repeated once more.

The described scheme of the mechanism of development of the underwater slope is undoubtedly idealized, since deviations from it can be found in nature. These deviations, which are not major, are due to particular factors influencing coastal zone development, such as fluctuations in the wave and current regimes, variations

in the topography of the underwater slope, differences in the geological structure of the shores and bottom, the sediment budget, the effect of mobile beach meso- and microrelief forms, and so on.

As we see, the mechanism of development of the abrasion profile of the underwater slope creates two main states represented by the concave and convex shapes of the curve in Fig. 4. And as in the case of the development of the different types of cliff, the gently sloping surface of the transverse profile corresponds to a constant, stable state of the shore, and the steep one to an unstable, dynamic state. In nature, there are, in addition to the two extreme states of the bottom profile already mentioned, many intermediate states created by the particular physical conditions obtaining along different stretches of the coast. These states can be ascertained by conducting a survey of the coastal zone.

The proposed scheme of short-term changes in the abrasion profile takes into account the effect on the cliff of the steepness and form of the profile of the underwater slope, which, owing to the high rates of bottom abrasion, can fluctuate quite rapidly. Field surveys on permanent sites reveal that the largest beaches are formed when the width of the platform is 130–150 metres and the angle of the underwater slope is less than 0.015–0.023 (in the 0–3 metre depth interval). The cliff is then abraded at a minimal rate or remains stable, the form of its profile is close to concave, and the cliff itself becomes gently sloping. As the steep concave part of the profile is being developed on the bottom (the angle of slope in the 0–3 m depth interval may reach 0.07–0.09), the cliff becomes more unstable and the steep convex form of the profile occurs more frequently owing to constant undercutting of the base. The cliff remains in this state until the convex profile of the bottom becomes relatively gentle in slope.

The model of the mechanism of abrasion profile development in the coastal zone fits in quite well with the results of long-term observations on the Black Sea–on shores in the regions of Odessa, Cape Burnas and Bel'bek River delta, and it is borne out by the data of laboratory modelling of an abrasion profile in the flume facility at the University of Odessa.

However, it is still very difficult to make a sufficiently reliable multifactorial analysis of abrasion profile development. Therefore appropriate constraints were imposed when formalizing the proposed model. Nevertheless, it is already possible to assess the qualitative influence of certain micro- and mesorelief forms near the water's edge (on the beach) on the dynamics of an abrasion profile which is made up of easily eroded argillaceous rocks.

As we now know [2], sandy beaches are characterized by rhythmic features called offsets[1]. Under their influence the width of the beach fluctuates with every storm. At intervals of 100–700 metres, depending on the size of the offsets, stretches of narrow beach corresponding to the concavity of the offset alternate with stretches of wide beach [6, 7], which correspond to the convexity of the offset. The difference in width under the conditions obtaining in the study region may 10–30 metres, and sometimes even more.

In the course of their development offsets migrate along the shore, following the pattern of littoral drift. This means that during one or several storms stretches of wide and narrow beach shift along the coast [1, 6].

Observation of the movement of an offset along a shore fronted by a convex underwater slope corresponding to an environment in which cliff abrasion is inhibited reveals that the inhibition is most pronounced when the bulge of the offset is situated in front of the cliff. The advent of the concavity of the offset may lead to higher rates of cliff erosion than usual.

When offsets move along a shore fronted by a concave steep underwater slope profile marking an environment of heightened cliff abrasion activity, the process of abrasion profile evolution is more complex. Generally speaking the passage of a wide stretch of beach leads to a reduction in the normally high rate of cliff erosion and hence to a drop in the rate of bench abrasion. As a result it takes longer for one cycle of the abrasion process to be succeeded by the next. The passage of the convexity of an offset usually causes complete erosion of the beach, the very rapid excavation of an abrasion platform, accelerated bench and cliff abrasion, and therefore a reduction in the time required for one cycle to replace another.

The mechanism of abrasion profile evolution in the coastal zone revealed by many years of fixed-site observations makes it possible to explain more fully and more reliably the unevenness of the abrasion rate in time and space, the fluctuations in the size of beaches and the amount of sediment they contain, the variations in the steepness of the bottom gradients and the form of the profile of the cliffs and underwater slope, and the dynamics of the shoreline.

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[1] Translator's note. The Russian word used is **offsety** [оффсеты], which is defined in the only Russian dictionary in which it occurs as: "Staggered oblique cusps or small, temporary spits measuring up to several tens of metres. They are formed when the waves approach the shoreline at an angle of less than 45°. They may consist of both sandy, pebbly and even boulder material. They constitute a miniature analogue of spits of the Azov type."

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